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Some observations on the application of optical spatial filtering techniques to motion picture printing

No. 1969/18

Research Department, Engineering Division
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RESEARCH DEPARTMENT

SOME OBSERVATIONS ON THE APPLICATION OF OPTICAL SPATIAL FILTERING TECHNIQUES TO MOTION PICTURE PRINTING

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(PH-34)

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SOME OBSERVATIONS ON THE APPLICATION OF OPTICAL SPATIAL FILTERING TECHNIQUES TO MOTION PICTURE PRINTING

SUMMARY

A previous report[1] *considers the application of spatial filtering techniques to the process of down-printing from the 35 mm to the 16 mm film format. This present report considers the use of a graded filter in the Fourier plane and discusses the limitations in the use of this technique, in conjunction with an incandescent light source, for the enhancement of fine detail.*

1. INTRODUCTION

The possibility of enhancing fine detail in the process of down-printing from a 35 mm to a 16 mm film format by using the technique of 'spatial filtering' has been described in detail in a previous report.[1] The present report discusses some results obtained by using such a system and examines its practicability.

In most applications of the spatial-filtering technique coherent laser radiation is used as the light source. In the present application, however, the use of laser radiation is open to several objections. The most fundamental of these is that colour film stock is designed for exposure to 'white' illumination in which all wavelengths covering the visual spectrum are present; each of the three dye layers on the film is effectively sensitive to radiations covering different limited ranges of the spectrum so that information corresponding to the three colour-separation images (red, green and blue) are separately recorded or transferred from the negative film to the positive print (although in practice there is a certain degree of 'cross-talk' between these three information channels). If the use of laser radiation is to be considered in colour film printing, at least three different wavelengths must be used, chosen to expose each of the dye layers on the print stock without increasing the interchannel cross-talk. This implies the use of three separate lasers* together with an optical system for combining their outputs into a single beam. The use of three separate sources would impose a problem in maintaining their relative outputs at the correct levels; any imbalance between the intensity of the three sources would give rise to a colour cast on the positive print, and the effect would be exaggerated by the high 'gamma' of the print stock. A further objection, which is by no means trivial, is the complexity of the laser system compared with the incandescent lamp normally used as a light source in film printing. It must be remembered that the intended final product of a printer employing the system is a 16 mm film colour print, conventional in all respects except for an enhancement of picture sharpness, and that there is a commercial limit to the degree of printer complexity that can be permitted for the achievement of this one benefit.

In considering a practical system of obtaining enhancement of fine detail by using the spatial-filtering technique, it was thought that the use of laser radiation was ruled out by the considerations discussed above. The results described in Section 4 of this report were obtained using an incandescent source (see Section 3); restrictions imposed by the limited light flux available from such a source are discussed in Section 5.

2. SUMMARY OF SPATIAL FREQUENCY FILTERING CONSIDERATIONS AS APPLIED TO FILM PRINTING

If a transparency is illuminated with a parallel beam of coherent light (of necessity monochromatic) the spatial distribution of the complex radiation amplitude** in the lens focal plane remote from the object corresponds to the Fourier transform of the spatial distribution of the complex amplitude of the radiation leaving the object itself. By placing a 'filter' in this 'Fourier plane' and arranging that the filter has a suitable spatial distribution of its amplitude and pahse characteristics, the complex amplitude distribution in the Fourier plane can be modified in a controlled manner, and the image (assumed to be real) formed by the lens possesses a spatial distribution of complex amplitude corresponding to this modification. When an incandescent light source is used to provide object illumination, however, the beam of light falling on the transparency is not coherent, being formed by the collimation of a cone of radiation emerging from a pinhole of small but finite area. It is therefore no longer possible to describe the spatial distribution of radiation in the object and Fourier planes in terms of complex amplitude, but only in terms of intensity (the intensity at any point is the sum of the squares of the amplitudes of the light fluxes reaching that point from each elementary area of the finite source). In one sense this is no disadvantage as neither the eye nor photographic film is sensitive to phase components. They both react only to the intensity of the radiation falling upon them. Spatial variations of film thickness still have to be considered, however, as their presence causes local curvature of the film surface; this gives rise to refraction effects which modify the light distribution in the Fourier plane and thus may produce effects in the image plane when spatial spectrum correction is attempted. In principle it should be possible to utilize these refraction effects to obtain added fine-detail correction in the present application of the spatial filtering technique. In practice, however, this possibility is excluded by the appearance of a very pronounced granular background in the image, which occurs because the surface of colour negative film stock is deliberately roughened to prevent interference effects ('Newton's rings') which can otherwise occur during contact printing. These refraction effects have therefore to be eliminated by the use of 'wet-gate' printing methods in which the negative is immersed during the exposure period in a parallel-sided layer of liquid of the same refractive index as the film.

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* More recently ion lasers have become available which lase at several wavelengths simultaneously. They are expensive (≃£5000) and no information is available about the relative stability of the various spectral lines.

** The term 'complex amplitude' implies that the relative phases of components of the radiation have to be considered, as well as their scalar magnitudes. In the present case the amplitude distribution of the radiation leaving the object is complex because of variations in the thickness of the film which result from differing amounts of deposited dye or silver.

If a transparency is illuminated by a truly parallel beam of light any given (two-dimensional) sinusoidal spatial-frequency component in the object plane gives rise to a unique pair of points of illumination in the Fourier plane; thus accurate control of the spatial spectrum of the image may be obtained by the insertion of the appropriate filter in the Fourier plane. When, as in the present case, the object is illuminated by a beam of light which is not strictly parallel, being formed by using a 'pinhole' light source and a collimating lens, these points of illumination in the Fourier plane are replaced by displaced images of the pinhole light source. The degree of correction obtained, for a given spatial frequency, then depends on the average transmission of the filter in the Fourier plane over the areas of these displaced images. In addition an asymmetrical positioning of the filter in the Fourier plane, so that its centre of symmetry does not coincide with the optical axis of the system, can modify its effect on the resulting spatial spectrum of the image and may result in the appearance of objectionable low-frequency smearing effects in the image, particularly if a circular opaque stop is used as the filtering element: this asymmetry is inevitable in the present case for all the elementary Fourier-transform distributions corresponding to off-centre elementary areas of the pinhole light source. For these reasons it is apparent that the diameter of the pinhole images formed in the Fourier plane should be as small as possible relative to the scale of the Fourier light-pattern (that is, the scale of pinhole image deflections due to the spatial-frequency components in the object plane): the choice of a suitable light source for this purpose is discussed in the following section. It may also be noted that the use of a 'graded' filter of circular symmetry, having low transmission at its centre and a continuous increase in transmission towards its periphery, has been suggested[1] as likely to produce fine-detail enhancement without the appearance of the smearing effect mentioned above; the use of such a filter is considered in Section 4.

3. THE INCANDESCENT LIGHT SOURCE

The need for minimizing the diameter of the light-source images formed in the Fourier plane has been discussed in Section 2. This dimension is a function of the degree of angular spread within the collimated beam, which is in turn determined by the angle subtended by the pinhole light source at the centre of the collimating lens: a clear requirement therefore exists for this angle to be as small as possible. At the same time the total available flux is proportional to the solid angle subtended by the source at the centre of the collimating lens (see Section 5.3) and a compromise has therefore to be made between these two conflicting requirements. In addition, it is important for the intensity of the collimated beam to be uniform over the area intercepted by the object; the cone of radiation emerging from the source and falling on the collimating lens must therefore also have uniform intensity. Some means is therefore required to ensure uniformity of this cone of radiation by ensuring that the corresponding cone of radiation collected by the pinhole has uniform intensity distribution. This condition is not satisfied if an incandescent light source directly illuminates the pinhole: under these conditions the image of the source is superimposed on the wanted film image. Initially[1] uniformity of intensity was obtained by placing a diffusing screen between the source and the pinhole (Fig. 1(*a*)). Subsequently an arrangement was used (giving a considerable increase in the intensity of object illumination) in which an image of the incandescent source was formed on the pinhole. The aperture of the lens used for this imaging process was sufficient to include the required cone of radiation (Fig. 1(*b*)), and the polar characteristics of the source were such as to deliver the appropriate cone of radiation to the source-imaging lens. For the full aperture of the pinhole to be effective the image of the source must entirely cover the pinhole. In practice, the roughly circular crater of a 'concentrated-arc' lamp was used as the source, as its image can be made to cover the pinhole with relatively little overlap. A source of less convenient shape (e.g. a filament lamp) would need to be of greater power to achieve the same result, as only a small part of the image of the source would be covered by the pinhole: problems of cooling the source-imaging lens would then become extreme.

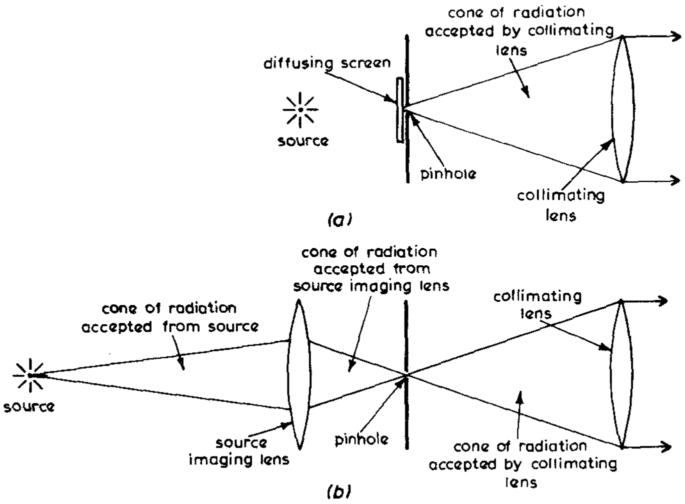
cone of radiation accepted by collimating lens
diffusing screen
source
pinhole
collimating lens
(a)
cone of radiation accepted from source imaging lens
cone of radiation accepted from source
collimating lens
source
source imaging lens
pinhole
cone of radiation accepted by collimating lens
(b)

Fig. 1 - Light source arrangements

To ensure uniformity of intensity distribution over the final image format all components in the optical system must be of very high quality and free from blemishes: this condition applies equally to the source imaging lens and to the glass bulb of the light source. Apart from the considerations discussed above, the type of concentrated-arc lamp used in practice as the light source can be obtained with a plane optical window in the bulb: the glass envelopes of most other lamps are relatively non-uniform and can give rise to striations in the wanted film image. This requirement for good uniformity of illumination over the image format represents a major practical difficulty in using the spatial filtering technique (or indeed any other process using well collimated object illumination).

4. THE EFFECT OF THE INTRODUCTION OF A GRADED FILTER ON THE RESOLUTION OF THE OPTICAL IMAGE AND THE RECORDED FILM IMAGE

4.1. The Effect of the Graded Filter on the Intensity of Light Reaching the Film

The use of a 'graded' filter, inserted into the Fourier plane in order to produce high-frequency enhancement in the image plane, has already been mentioned in Section 2. The degree of enhancement of resolution brought about by the use of such a filter will be examined by considering the case in which a sinusoidal spatial distribution of radiation amplitude, superimposed on a constant component, is present in the radiation immediately after leaving the object. This distribution is assumed to be one-dimensional and the pattern in the object plane therefore takes the form of a set of parallel bars. Furthermore, the point source from which the collimated illumination of the object is obtained is assumed to be so small that no significant change in the transmission factor of the graded filter occurs within the bounds of each image of this source in the Fourier plane. Under these conditions the intensity of illumination at any point in the image plane is the same (apart from a scale factor) as the intensity given by considering a single element of the source. In the Fourier plane three images of the source will appear; one image on the optical axis of the system corresponds with the constant component of the object-plane radiation amplitude distribution while a pair of images disposed on each side of the optical axis, along a line normal to the set of bars in the object plane, correspond to the spatially alternating component of the object-plane distribution. The separation of the displaced images from the optical axis is proportional to the spatial frequency (i.e. inversely proportional to bar spacing) in the object plane. The formation of the image may be considered as being due to radiation from these three Fourier-plane 'sources'; the image-plane amplitude may be obtained by considering the amplitude and phase of the components from a point in each Fourier-plane image corresponding to the same element in the original light source. Vector diagrams showing these components may be drawn in a form analogous to those used to describe the modulation of a radio-frequency signal. In Fig. 2(i) the vertical vector of length A represents the contribution from the on-axis Fourier-plane source while the inclined vectors of length $a/2$ represent the contribution from the off-axis Fourier-plane sources. As a point of observation in the image plane moves across the image of light and dark bars all three vectors shown in Fig. 2(i) rotate: relative to the vector from the on-axis source, the other two vectors rotate in opposite directions completing one revolution as one cycle of the bar pattern is traversed. As the point of observation of maximum amplitude in the image plane the vectors all reinforce as shown in Fig. 2(ii) while at the point of observation of minimum amplitude the vectors partially cancel as shown in Fig. 2(iii). The total excursion of amplitude is therefore $2a$ while the constant component is of amplitude A. The greatest and least amplitudes in the image plane ($A_{\max}$ and $A_{\min}$) are therefore:

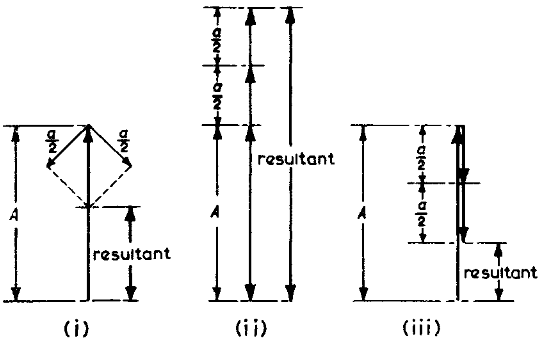

Fig. 2 - Vector diagrams of amplitude components in image plane

(i) General (ii) Maximum (iii) Minimum

$$\left.\begin{aligned} A_{\max} &= A + a \\ A_{\min} &= A - a \end{aligned}\right\} \qquad (1)$$

The greatest and least intensities in the image plane ($I_{\max}$ and $I_{\min}$) are:

$$\left.\begin{aligned} I_{\max} &= A^2{}_{\max} = (A + a)^2 \\ I_{\min} &= A^2{}_{\min} = (A - a)^2 \end{aligned}\right\} \qquad (2)$$

Hence the difference between the greatest and least intensities (ΔI) is seen to be:

$$\Delta I = I_{\max} - I_{\min} = 4Aa \qquad (3)$$

Suppose that a filter is inserted into the Fourier plane which alters the amplitude of the vector representing the contribution of the on-axis Fourier-plane source by a factor k(where $k<1$), so that its new value becomes kA, without affecting the amplitudes of the vectors representing the contributions of the off-axis Fourier-plane sources, which remain of length $a/2$ (see Fig. 3). The intensity corresponding to the constant component of the image radiation then

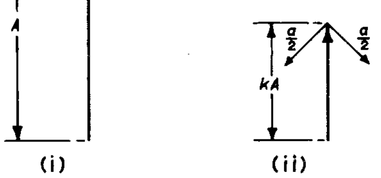

Fig. 3 - Vector diagrams showing effect of insertion of graded filter in Fourier plane

(i) Before insertion of filter (ii) After insertion of filter becomes $(kA)^2$: thus to restore the exposure of a film in the image plane to the value present before the insertion of the Fourier-plane filter an increase of exposure time of $1/k^2$ would be required. The greatest and least amplitudes in the image plane (A'_{max} and A'_{min}) are:

$$\left.\begin{aligned} A'_{max} &= kA + a \\ A'_{min} &= kA - a \end{aligned}\right\} \qquad (4)$$

The greatest and least intensities in the image plane (I'_{max} and I'_{min}) are now:

$$\left.\begin{aligned} I'_{max} &= (kA + a)^2 \\ I'_{min} &= (kA - a)^2 \end{aligned}\right\} \qquad (5)$$

while the difference ($\Delta I'$) between these intensities is:

$$\Delta I' = I'_{max} - I'_{min} = 4kAa \qquad (6)$$

The value of $\Delta I'$ shown in Equation (6) relates to the actual image intensity obtained after insertion of the Fourier-plane filter, without allowance for the required increase of exposure time. This allowance can be expressed as an increase in image intensity by a factor of $1/k^2$ (remembering $k<1$); taking this factor into account, the difference between the greatest and least intensities in the image plane ($\Delta I''$) is, from Equation (6)

$$\Delta I'' = \frac{4Aa}{k} \qquad (7)$$

An intensity enhancement factor F_I may be defined such that:

$$F_I = \frac{\Delta I''}{\Delta I} = \frac{1}{k} \qquad (8)$$

In order to achieve this degree of enhancement, a graded spatial filter must be used which reduces the overall image intensity by a factor of $1/k^2$: to restore the exposure of a film in the image plane to the original value, the exposure time must be increased by this factor, assuming reciprocity between intensity and exposure time.

4.2. The Effect of the Graded Filter on the Transmission Factor of the Developed Image Formed on the Film

4.2.1. The Film Characteristic

The characteristic relating the logarithm of the film exposure ($\log E$) and the resulting density (D) of the exposed film after development is substantially linear over a considerable range. The gradient of this linear portion of the characteristic is a function of the particular film stock under consideration and of the development process, and is characterized by the symbol γ (gamma). Such a relationship is shown by the full line in Fig. 4: for low exposures the relationship becomes non-linear in practice, as shown by the dotted line in Fig. 4.

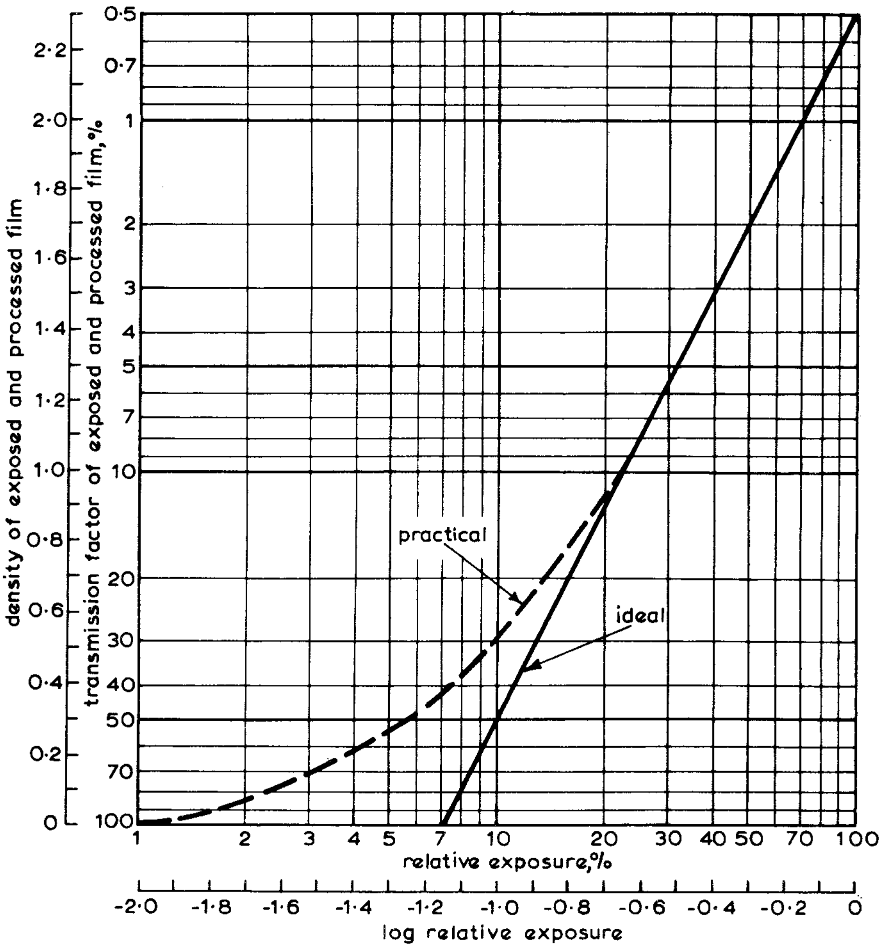

Fig. 4 - Film exposure characteristic

The equation of the full line in Fig. 4 may be written*

$$D = \gamma \log E + C \tag{9}$$

where C is a constant. Let the value of E be E_0 when $D = 0$; thus

$$C = -\gamma \log E_0$$

and Equation (9) becomes

$$D = \gamma \log \frac{E}{E_0} \tag{10}$$

The value E_0 represents a 'threshold' exposure level, below which no film exposure occurs. In practice the film non-linearity** in the low-exposure region has the effect that the true threshold value is reached at a lower level than shown in Equation (10): the value E_0 may however be conveniently retained and referred to as the 'extended exposure threshold'.

Remembering that

$$D = \log \frac{1}{T}$$

where T is the film transmission (defined so that for no exposure $T = 1$, i.e. the effects of film base and 'fog' are not included), Equation (10) may be written:

$$T = \left(\frac{E}{E_0}\right)^{-\gamma} \tag{11}$$

4.2.2. The Effect on Patterns of Low Modulation Depth

Suppose that the film exposure is so arranged that full exposure ($E = 1$) occurs with unity intensity ($I = 1$), referring to the equations in Section 4.1. Since exposure is directly proportional to intensity, Equation (11) becomes:

$$T = \left(\frac{I}{I_0}\right)^{-\gamma} \tag{12}$$

I_0 being the 'extended intensity threshold' below which no film exposure occurs, in the absence of film non-linearity. Before the application of spatial-frequency correction by means of a suitable graded filter the film transmission factor corresponding to the most exposed part of the bar pattern ($T_{\min}$) is given by:

$$T_{\min} = \left(\frac{I_{\max}}{I_0}\right)^{-\gamma}$$

$$= \left[\frac{(A+a)^2}{I_0}\right]^{-\gamma} \quad \text{from Equation (2)}$$

$$= \frac{(A+a)^{-2\gamma}}{I_0^{-\gamma}} \tag{13}$$

If $a/A \ll 1$ so that second-order and higher powers of a/A may be neglected, Equation (13) reduces to:

$$T_{\min} = \frac{A^{-(2\gamma+1)}}{I_0^{-\gamma}} (A - 2\gamma a) \tag{14}$$

Similarly, the film transmission factor corresponding to the least exposed part of the bar pattern ($T_{\max}$) is given by:

$$T_{\max} = \left(\frac{I_{\min}}{I_0}\right)^{-\gamma} = \frac{A^{-(2\gamma+1)}}{I_0^{-\gamma}} (A + 2\gamma a) \tag{15}$$

Hence the difference between the transmission factors corresponding to the extremities of the bar pattern (ΔT) is given by:

$$\Delta T = T_{\max} - T_{\min} = \frac{A^{-(2\gamma+1)}}{I_0^{-\gamma}} . 4\gamma a \tag{16}$$

After the application of the spatial frequency correction, discussed in Section 4.1, followed by an increase of exposure by a factor of $1/k^2$ to restore the exposure of the film to the previous value, the minimum and maximum transmission factors ($T'_{\min}$ and $T'_{\max}$) corresponding to the most and least exposed parts of the bar pattern image become:

$$T'_{\min} = \left[\frac{(I'_{\max})/k^2}{I_0}\right]^{-\gamma} = \left[\frac{(kA+a)^2}{I_0 k^2}\right]^{-\gamma} \tag{17}$$

and

$$T'_{\max} = \left[\frac{(I'_{\min})/k^2}{I_0}\right]^{-\gamma} = \left[\frac{(kA-a)^2}{I_0 k^2}\right]^{-\gamma} \tag{18}$$

by substitution from Equation (5).

The difference between these values ($\Delta T'$), with the provision that $a/kA \ll 1$, therefore becomes:

$$\Delta T' = \frac{(kA)^{-(2\gamma+1)}}{(I_0 k^2)^{-\gamma}} . 4\gamma a$$

$$= \frac{1}{k} . \frac{A^{-(2\gamma+1)}}{I_0^{-\gamma}} . 4\gamma a$$

$$= \frac{1}{k} . \Delta T \tag{19}$$

$$\text{Thus} \frac{\Delta T'}{\Delta T} = F_T = \frac{1}{k} \tag{20}$$

where F_T is the transmission enhancement factor, analogous to the intensity enhancement factor F_I (see Equation (8)) which refers to the optical image formed on the film. The equality of F_I and F_T shows that for small modulation depths, where the approximations involved in deriving equations (14) and (19) are valid, the same degree of enhancement appears in the film image (irrespective of the gamma value of the film) as was present in the optical image causing the film exposures.

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* All logarithms are assumed to be to the base 10.

** Referred to in the logarithmic co-ordinates of Fig. 4.

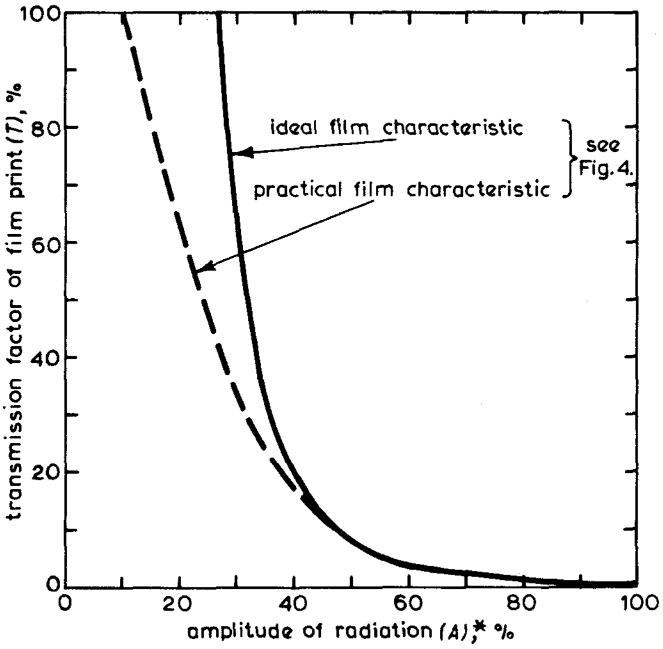

Fig. 5 - Relation between transmission factor of film print and amplitude of incident radiation

* 100% corresponds to maximum film exposure (see footnote below)

4.2.3. The Effect on Patterns of Large Modulation Depth

For patterns of large modulation depth, where the approximations used in obtaining Equations (14), (15) and (19) are not valid, the mathematical derivation of the transmission enhancement factor becomes complex: it is more convenient to illustrate the behaviour of this factor by using a particular numerical example. Expressing Equation (12) in terms of amplitude, it can be seen that:

$$T = \frac{I_0 \gamma}{A^{2\gamma}}$$

For the case in which $\gamma = 2{\cdot}0$ and $I_0 = 0{\cdot}07$*

$$T = \frac{0{\cdot}0049}{A^4} \qquad (21)$$

This relationship is shown by the full line in Fig. 5 and is based upon the ideal characteristic of Fig. 4: the dotted lines in this figure shows the corresponding relation for the 'practical' film characteristic shown in Fig. 4. It can be seen that, in the case of the relationship given by Equation (21), no exposure of the film occurs for amplitudes of less than about 28% of the maximum value, while a print transmission of 5% is obtained for an amplitude of about 56% of the maximum value. This extreme nonlinearity of the relationship between print transmission and the amplitude of the incident radiation implies that the value of the transmission enhancement factor F_T depends markedly on the actual greatest and least amplitude values both before and after spatial-frequency enhancement; in other words the value of F_T depends on the values of the quantities A and a (Equation 1) and k (Equation 4). This dependence is illustrated in Fig. 6; here the values of k has been taken as 0·5 and two values of A (31·6% to correspond to a film transmission of 50%, and 50% which corresponds to a film transmission of 8%) have been taken. The curves relate to the ideal film characteristic shown in Fig. 4; corresponding relationships may be derived for other characteristics. It can be seen from Fig. 6 that the relationship between F_T and k derived in Section 4.2.2 holds only for very small values of a. The abrupt discontinuity in the relationship occurs when the minimum amplitude of the radiation falling on the film after the application of the Fourier-plane filter (i.e. the quantity $(kA-a)$ in Equation 4) corresponds, after the appropriate exposure adjustment by a factor of $1/k^2$, to the threshold exposure level E_0 (Equation 11). Amplitude values lower than this value have no effect on the film, and the value of F_T falls because of the decreasing effect of incident radiation on the transmission of the film as the exposure approaches its maximum value.

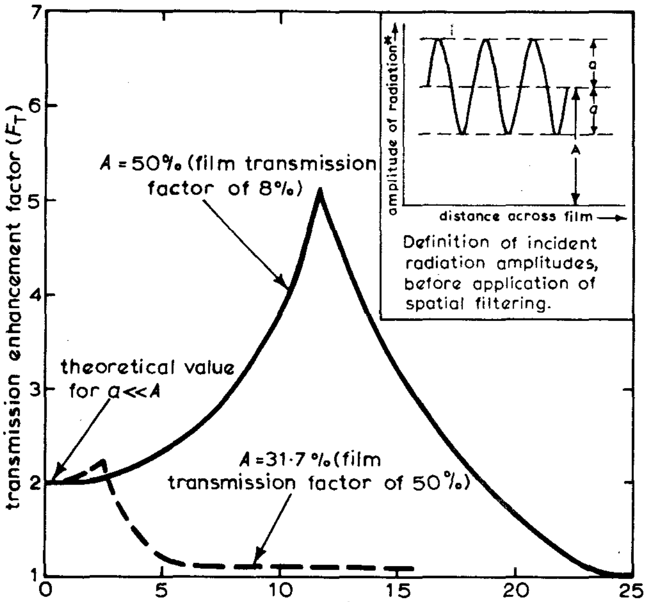

Fig. 6 - Examples of the relation between the transmission enhancement factor and the amplitude excursion of the incident radiation

* Amplitude = 100% for maximum film exposure (see footnote at bottom of Column 1)

The curves in Fig. 6 have been terminated at the point at which the value of the factor $(kA-a)$ is zero. For values of a which give rise to negative values of this factor, a 'frequency doubling' effect will be apparent in both the visual and recorded images of the bar pattern, since the eye and the photographic process are both sensitive only to intensity and take no account of the phase of incident radiation. This frequency doubling effect will not however be visible on the recorded film image until the intensity of the subsidiary maximum appearing in the nominally dark areas of the pattern incident on the film reaches the threshold exposure level. It should however be remembered that the threshold exposure level of a practical film stock is lower than the 'extended' value E_0 (compare the full and dotted curves in Fig. 5) and the frequency doubling effect will become noticeable on the recorded image for relatively small intensity values of the subsidiary maximum. The onset of this effect does not represent a limitation to the effectiveness of spatial filtering if deficiencies in the object (i.e. the negative film) or the optical system are being compensated, because in this case modulation depths in the image plane greater than 100% would not be involved: however if compensation for the characteristics of the print stock is also being attempted this effect does impose a limit, since in this case modulation depths greater than 100% may well be encountered in the image plane.

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* These values give a print density of 2·3 (above base and fog) for maximum exposure, and are typical of practical exposure conditions.

Film resolution is usually described in terms of the 'modulation transfer factor' (m.t.f.) which expresses the ratio between the peak excursion of the transmission factor to the mean transmission factor. Using the nomenclature adopted in Equations (14) and (15) the m.t.f. before the application of spatial frequency correction (M) is given by

$$M = \frac{T_{\mathrm{max}} - T_{\mathrm{min}}}{T_{\mathrm{max}} + T_{\mathrm{min}}} \qquad (22)$$

while the m.t.f. after the application of spatial frequency correction (M') is referring to Equations (17) and (18) given by

$$M' = \frac{T'_{\mathrm{max}} - T'_{\mathrm{min}}}{T'_{\mathrm{max}} + T'_{\mathrm{min}}} \qquad (23)$$

From Equations (22) and (23) a 'modulation enhancement factor' F_{M} may be defined, where

$$F_{\mathrm{M}} = \frac{M'}{M} \qquad (24)$$

From the definition of the transmission enhancement factor F_{T} (see Equation (20)) it is apparent that

$$\begin{aligned} F_{\mathrm{M}} &= F_{\mathrm{T}} \cdot \frac{T_{\mathrm{max}} + T_{\mathrm{min}}}{T'_{\mathrm{max}} + T'_{\mathrm{min}}} \\ &= F_{\mathrm{T}} \cdot \frac{T_{\mathrm{mean}}}{T'_{\mathrm{mean}}} \qquad (25) \end{aligned}$$

where T_{mean} and T'_{mean} are the mean transmission factors of the bar patterns before and after the application of correction respectively. For a linear system these mean values would remain equal for all degrees of correction and the modulation and transmission enhancement factors would also be equal. In the present case, however, the relationship (Fig. 5) between the radiation amplitudes (which are themselves linearly related to the degree of applied correction) and the corresponding film transmission factors is grossly non-linear and equality between the quantities F_{T} and F_{M} is no longer obtained. Fig. 7 shows the relation between the modulation enhancement factor (F_{M}) and the amplitude excursion before the application of spatial filtering for the same two conditions used (see Fig. 6) to examine the behaviour of the transmission enhancement factor. It can be seen that the value of the modulation enhancement factor falls continuously for increasing values of amplitude excursion, the initial rise in the value of the transmission enhancement factor being more than offset by the increase in the mean transmission factor after the application of spatial frequency correction (T'_{mean} in Equation (25)).

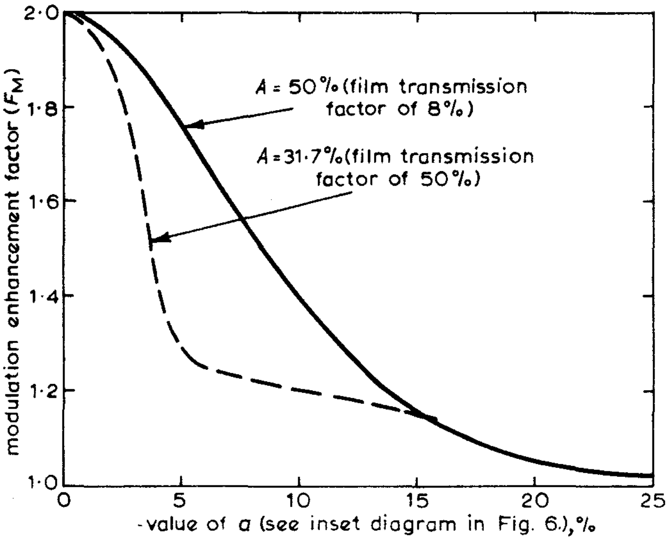

Fig. 7 - Examples of the relation between the modulation enhancement factor and the amplitude excursion of the incident radiation

4.2.4. Comparison of Theoretical and Experimental Results

The optical arrangement used for making experimental 16 mm down-prints from 35 mm negative material is shown in Fig. 8. This arrangement was basically the same as given in Fig. 10 of Reference 1 (a magnified image of the intensity distribution in the first Fourier plane being formed by the lens L4 in the 'second Fourier plane', which contained the graded filter) except that a different incandescent source was used (see Section 3). The increased light flux from the source was utilized to reduce the size of the pinhole image in the Fourier plane, the radius of the pinhole image in this plane corresponding to an image displacement* equivalent to a video frequency** of approximately 0·9 MHz. The relationship between the transmission of the graded filter and radial distance from the centre of the filter is shown by the full line in Fig. 9: the dotted line in this figure shows the average transmission over the pinhole image area, the abscissa values in this case referring to image displacement. The average transmission factor for zero displacement can be seen to be approximately 20%, corresponding to a required exposure increase

* For a given spatial frequency in the object plane, the image displacement depends on the wavelength of the incident light. A wavelength of 435 nm, at which the print stock used in obtaining the experimental results had maximum sensitivity, is assumed throughout this section.

** The video frequency values refer to the frequencies that would be obtained if the film image were scanned using the 625-line, 50 fields per second system.

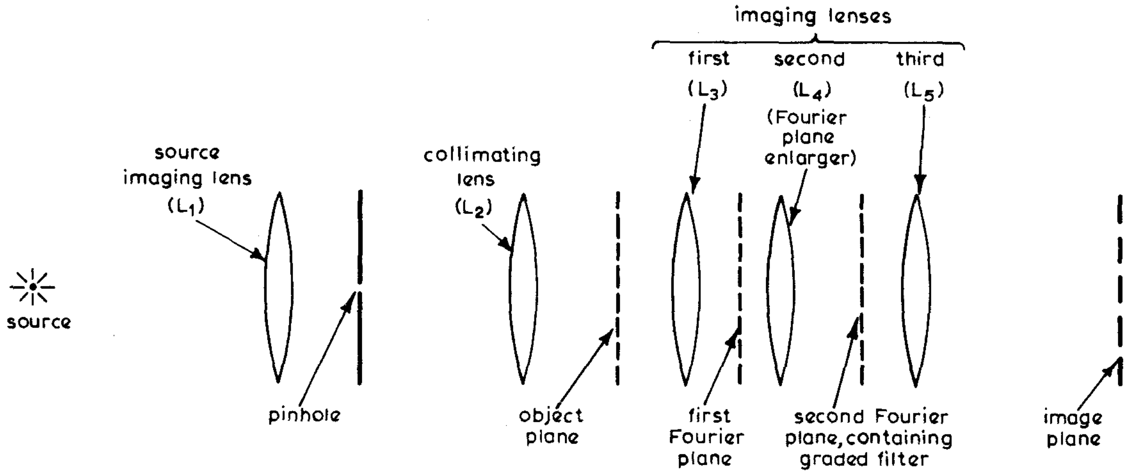

Fig. 8 - Experiment optical arrangement
(not to scale)

by a factor of five on insertion of the graded filter; in practice, however, it was found that a quadrupling of the exposure time compensated for the insertion of the filter. The reason for this discrepancy between theory and practice is not certain, but it may be caused by the transmission of 'image-forming' light from object to image by paths other than directly through the spatial filter, due to scattering within the collimating lens (L_2 in Fig. 8) or the negative film image in the object plane.

The relationships between the print film-stock exposure and the transmission of the corresponding area of the recorded image obtained experimentally are shown by the thick lines in Fig. 10. For relatively high exposure values the results obtained with and without the use of the spatial filter are very similar, showing that equality of exposure has been achieved in the two cases. For low exposure values both relationships (thin lines in Fig. 10) appear to be asymptotic to film-transmission-factor values less than 100%, the value being lower when the spatial filter was inserted than when the filter was not present. These measurements of film characteristic were made using the central 'grey scale' wedge of Test Card 'C', which occupies a relatively small area of the total picture area, and the result described above is probably caused by the presence of veiling glare from the lenses L_3 and L_4 in Fig. 8. The intensity of the veiling glare would not be significantly affected by the introduction of the spatial filter, and it would therefore have a proportionally greater effect on the recorded film-image because of the longer exposure time required for this condition.

Calculations have been made of the enhancement of high-frequency detail produced by use of the spatial filter whose characteristics are shown in Fig. 9. The initial maximum and minimum light-intensity values in the bar patterns formed in the image plane have been inferred from the corresponding transmission values in the recorded image obtained without the use of the spatial filter (the black circles in Fig. 11*): in this way the response/frequency characteristic of the positive film stock was included in the 'overall' characteristic of the experimental reduction printing process. The appropriate film characteristic curves of Fig. 10 have been used, both for the procedure described above and for the calculation, using the method described in Section 4.2.3, of the effect of the graded spatial filter. It should be noted that the assumptions made initially in the derivation of this method of calculation (see Section 4.1) are not strictly applicable in the practical case under consideration; nevertheless there is substantial agreement between the calculated results and those obtained experimentally when the spatial filter was inserted (open triangles and open circles respectively in Fig. 11) although a rather greater degree of correction than predicted was obtained at the higher spatial frequencies. It can be seen that the reduction in resolution which occurs as spatial frequency is increased arises principally because of a rise in the minimum transmission factor values, and that the application of spatial filtering enhances the resolution by reducing these values. The maximum transmission factor values are largely determined by the exposure of the film to veiling glare, as discussed above, and the use of spatial filtering cannot therefore increase these values.

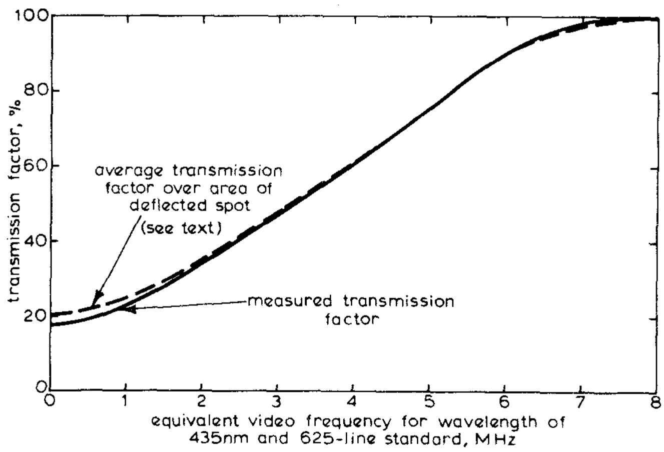

Fig. 9 - Characteristics of graded spatial filter

Fig. 12(*a*) shows the film print transmission factors contained in Fig. 11 re-plotted in terms of the corresponding modulation transfer factors. It can be seen that, even at very low frequencies, an m.t.f. of unity is not achieved, owing to the unwanted exposure of the nominally white picture areas. The enhancement of high-frequency detail with the application of spatial frequency filtering is shown in Fig. 12(*b*) in terms of the modulation enhancement factor F_M (see Equation (24)); it can again be seen that at the higher frequencies the degree of correction obtained in practice is higher than predicted.

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* See second footnote on page 7.

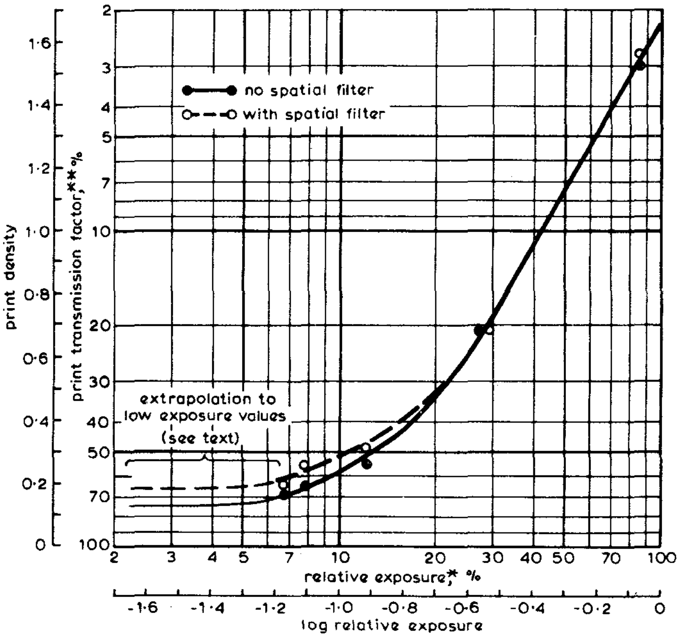

Fig. 10 - Experimentally achieved print exposure characteristic

* 100% relative exposure corresponds to unexposed negative film base

** 100% print transmission corresponds to unexposed print film base

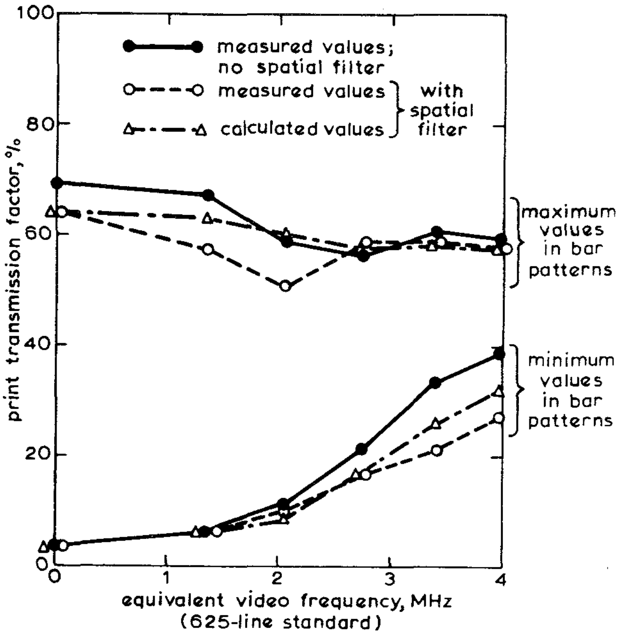

Fig. 11 - Film print transmission factors

(100% transmission corresponds to unexposed film base)

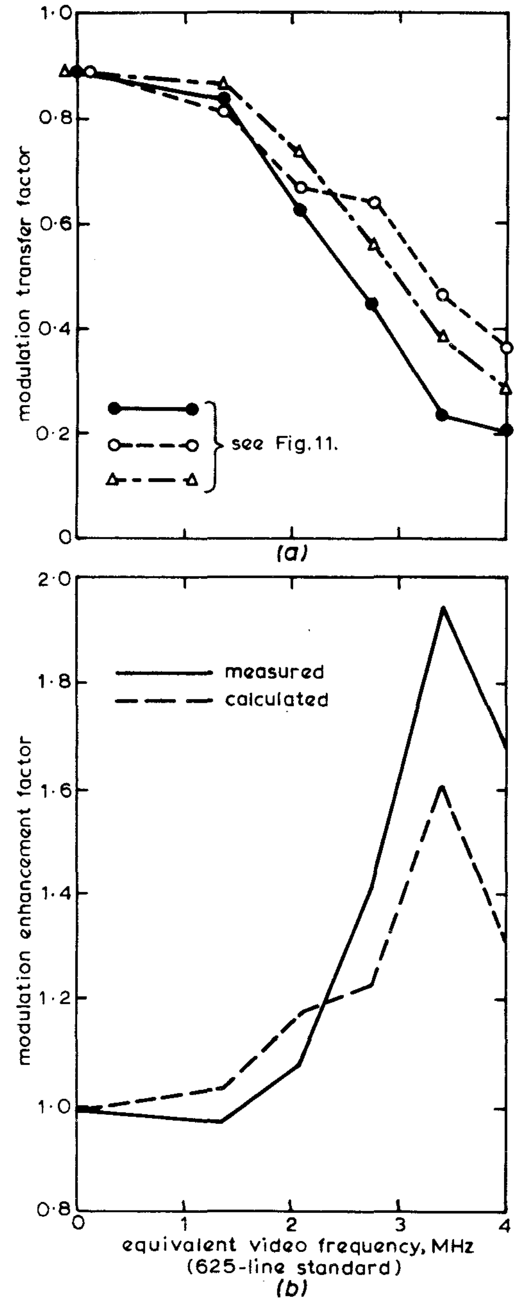

Fig. 12 - Film print modulation characteristics

(*a*) Measured and calculated modulation transfer factors

(*b*) Measured and calculated modulation enhancement factors

5. PRACTICAL FILM EXPOSURE CONSIDERATIONS

5.1. Experimentally-achieved Exposure Times

Motion-picture printing machines commonly run at twice the conventional frame speed and make use of half the duty cycle for the actual exposure of the film: under these conditions an exposure time of 1/100 second is available. Using conventional balck-and-white positive print stock,* an exposure time of one second was required in the experimental arrangement described in Section 4.2.4, in the absence of the graded spatial filter; this time increased to four seconds when the filter was inserted. It can be seen from Figs. 11 and 12(*a*) that the spatial filter used experimentally did not give complete correction for the overall response/frequency characteristic of the printing process. On the other hand, Fig. 9 shows that the radius of the filter was rather greater than required for correction within the restricted video frequency range of up to 5½ MHz so that the attenuation of light through its centre was unnecessarily great for the degree of correction obtained; (this latter consideration does not, however, take into account that fact that if spatial frequency correction is applied to colour-film printing, operation in red light must also be considered. The abcissa scale of Fig. 9 refers to blue light (435 nm): if red light (680 nm)[*] is considered, a pinhole-image deflection equal to the radius of the filter is obtained corresponding to a video frequency of only 5½ MHz.) These considerations indicate that a somewhat greater degree of high-frequency correction than was achieved in the present experiment could be obtained (at least in blue light) using a filter which required a fourfold increase in exposure time on its insertion. Although this degree of correction would be worth while the required exposure time would be some 400 times longer than is at present used in film printing. The correspondingly slow printing speeds would be totally impracticable in the operational production of film prints.

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* Kodak type 5366: this has emulsion characteristics identical to type 5302 but laid down on a grey base. 35 mm film was used experimentally in a 'still' camera carcase: Kodak type numbers 7366 and 7302 refer to the same film-stock material cut to 16 mm gauge.

The exposure time may be reduced by increasing the intensity of the illumination of the object (the film negative). Using an incandescent lamp as the prime light source,[**] this may be achieved by raising its operating temperature or by increasing the effective solid angle subtended by the illuminated pinhole at the centre of the collimating lens. In addition it is possible to simplify the optical arrangement and thus improve its transmission factor. These considerations are discussed in Sections 5.2, 5.3 and 5.4.

5.2. Increase in Operating Temperature of Source

An increase in temperature of a black-body radiator from 3000 K (the operating temperature of the concentrated-arc lamp used for obtaining the experimental exposures) to 6000 K would increase the light flux at a wavelength of 435 nm by a factor of some 240 times. This indicates that in principle a very substantial reduction in exposure time may be achieved, when using blue-sensitive black-and-white print-film stock, by raising the temperature of the source by this amount. When dealing with colour print stock,[***] however, the increase in intensity for all wavelengths to which the print stock is sensitive must be considered. At a wavelength of 680 nm (see first footnote below) a flux increase of only some 35 times is obtained by increasing the temperature of the source from 3000 K to 6000 K, and the obtainable reduction in exposure time is correspondingly less: the greater flux increase at shorter wavelengths has to be compensated by a blue-absorbing ('colour temperature lowering') filter so that an overall blue cast is not produced in the recorded image.

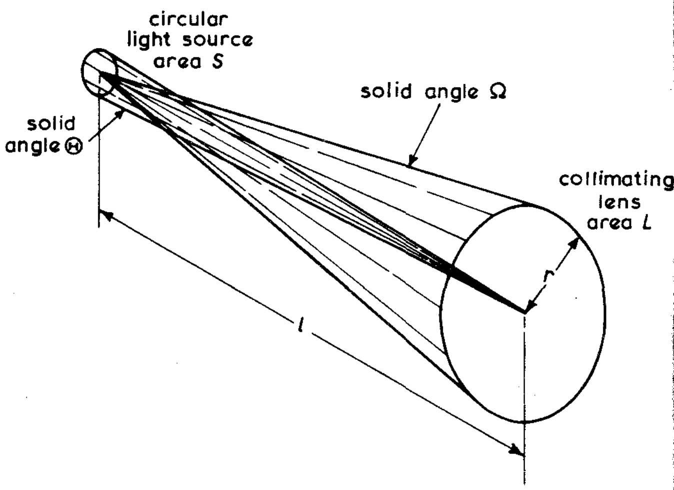

Fig. 13 - Illustration of light source and collimating lens

The use of a xenon arc lamp[*] would enable operation at a colour temperature of about 6000 K to be achieved, but because all practical light sources have absolute energy outputs lower than predicted by the black-body equation (Planck's relation), to extents which vary considerably between individual types of sources, it is not possible to give a precise value to the reduction in exposure time that may be obtained by the use of this type of source.

5.3. Increase in the Effective Solid Angle Subtended by the Source

Fig. 13 shows a circular light source of area S situated at a distance l from a collimating lens of radius r and area L. If it is assumed that l is much greater than r, then the solid angle (Ω) subtended by the lens at the source is given by

$$\Omega = \frac{L}{l^2}$$

furthermore, the projected area of the source along any direction within the solid angle Ω is equal to the area S of the source itself. The flux reaching the lens is then given by:

$$F = n.S\Omega = \frac{nSL}{l^2} = n'\frac{S}{l^2} = n'\Theta$$

where n and n' are constants and Θ ($= S/l^2$) is the solid angle subtended at the centre of the lens by the source. It can therefore be seen that the light flux reaching the collimating lens is proportional to this solid angle. If this solid angle is increased so as to increase the intensity of illumination of the film negative, however, the pinhole image diameter in the Fourier plane will also be increased: the need for keeping this dimension as small as possible has already been discussed (Section 2). The effective radiating area of the source (and therefore the effective solid angle subtended by it) could, however, be increased without affecting the spatial filtering operation by increasing the number of pinholes in the focal plane of the collimating lens, rather than increasing the diameter of a single pinhole. In the Fourier plane the undeflected image corresponding to each pinhole will be surrounded by deflected images, and a graded spatial filter centered on each undeflected image would be required. If the image deflection corresponding to the highest video frequency is greater than the pinhole image radius by a factor P, the pinholes themselves must be separated from each other by a distance of at least $2q(P+1)$, where q is the radius of each pinhole, to avoid overlapping of the first-order patterns in the Fourier plane. It should be remembered that the cone of radiation emerging from each pinhole and falling on the collimating lens must be uniform in intensity in order to obtain uniform illumination of the film negative in the object plane (see Section 3).

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[*] The cyan-forming layers of typical print film stocks are most sensitive to this wavelength.

[**] The use of laser radiation is discussed in Section 1.

[***] In conventional film printing equipment, using tungsten light sources (having a colour temperature of about 3000 K) very similar exposure periods are required for both black-and-white and colour print film stocks. The two cases are therefore directly comparable.

[*] A carbon arc source is not considered suitable because of its frequent need of attention and the relative instability of its intensity.

An extension of the system of multiple sources described above, which would give a considerable increase in the intensity of illumination of the film negative, is practicable if the enhancement of high spatial frequencies is restricted to one picture axis. In this case the pinhole in the focal plane of the collimating lens can be replaced by a narrow slit, the contours of equal transmission in the spatial filter being parallel to the image of the slit in the Fourier plane. Illumination of the slit may be achieved by forming on it the image of a straight filament, greater object illumination resulting because of the more efficient use of radiation from this source. This technique confers no advantage in the case of point sources (arc lamps) as the use of a pinhole represents an efficient method of using such sources (see Section 3).

The disadvantages associated with using collimated light for illuminating the film negative have been discussed in Section 3. With the use of multiple sources in the focal plane of the collimating lens the illumination is no longer strictly collimated, since each source produces a collimated beam of radiation differing in direction of travel to all the other collimated beams. The occurrence of defects in the final film print because of blemishes in the optical system is therefore likely to be a less severe problem than if only one source is used.

5.4. Improvement of the Efficiency of the Optical System

The overall spectral response of the optical system used for making the experimental 16 mm downprints is shown by the full line in Fig. 14. The maximum transmission factor is 56% and is only 25% at the effective wavelength for exposure of the film stock (435 nm). The dotted line in Fig. 14 shows the response that would have been obtained if all the lenses had the characteristic of the best lens used in the arrangement, and it can be seen that a significant improvement in transmission factor would have been obtained. A further improvement may in principle be made by omitting lenses L_4 and L_5 (Fig. 8), in which case lens L_3 would form the final image of the negative film. The response that would be obtained under these conditions is shown by the chain-dotted line in Fig. 14; at 435 nm the transmission factor is more than double the value in the practical system, while the maximum transmission factor is increased by a factor of about 1·3. The graded spatial filter would have to be introduced in the focal plane of lens L_3, and the small scale of the Fourier-plane intensity pattern in this plane might pose a significant problem.

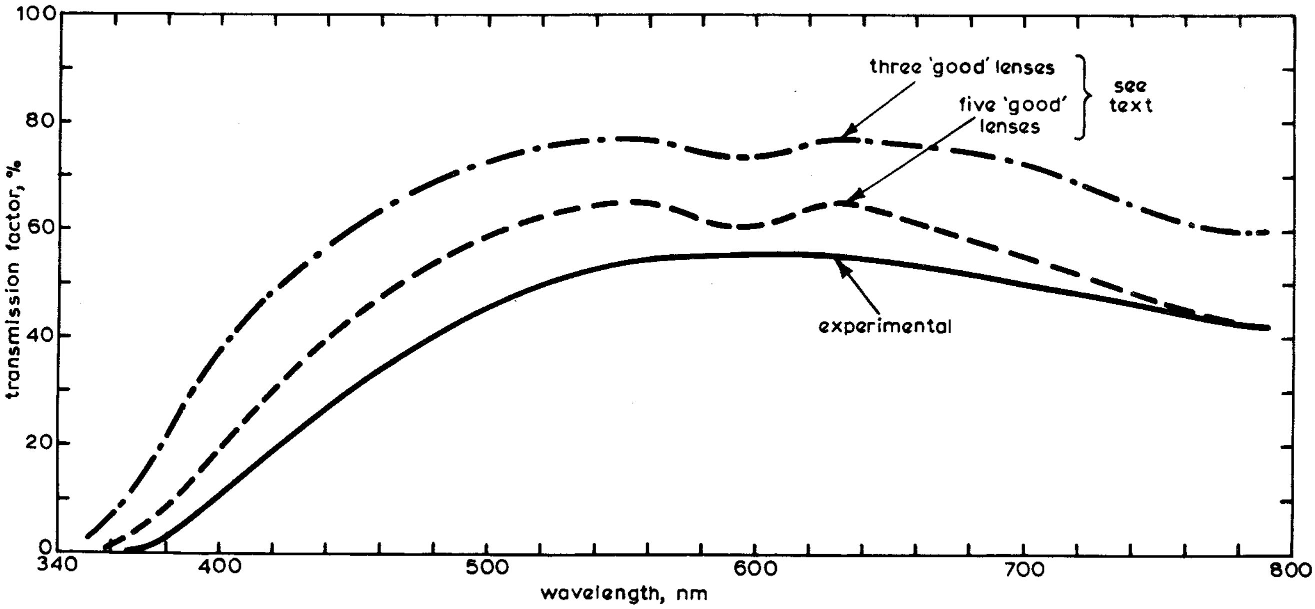

Fig. 14 - Spectral responses of optical systems

6. CONCLUSIONS

A measure of enhancement of fine picture-detail has been obtained experimentally by the use of the 'spatial filtering' technique in an optical system for 35 mm to 16 mm film reduction printing, without the appearance of obejctionable low-frequency 'smearing' effects. A graded filter was used in the Fourier plane and object illumination was derived from a concentrated-arc incandescent lamp. The achieved degree of enhancement was consistent with the predictions given by a simplified theoretical model of the spatial filtering process; it did not however fully compensate for the observed overall loss in resolution caused by losses in the film negative, optical system and positive print stock.

A very much longer exposure time was required than is normally used in film printing. Although it would be possible to reduce this exposure time to a certain extent by modifying the design of the incandescent light source and by simplifying the optical system, considerable constructional and operational complexity would be involved in obtaining expsoure times approaching the normal values. Satisfactory exposure times could be achieved by using laser radiation, but the use of such radiation (particularly in the printing of colour film) is also open to the objection of complexity. It would therefore seem impracticable to use the spatial filtering technique for enhancing the sharpness of 16 mm film reduction prints unless the consequent increase in complexity and cost of the printer were tolerable.

7. REFERENCE

1. Spatial filtering applied to film printing: some fundamental considerations. BBC Research Department Report No. PH-20, Serial No. 1968/41.

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